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Title:	Underground Siting of Small Modular Reactors: Rationale, Concepts, and Applications
Author(s):	C. W. Myers, Affiliate, N-DO, LANL J. M. Mahar, Professor, Idaho State University
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UNDERGOUND SITING OF SMALL MODULAR REACTORS: RATIONALE, CONCEPTS, AND APPLICATIONS

ABSTRACT

Small modular reactors (SMRs) sited 100 to 300 meters deep in underground chambers constructed in bedrock having favorable geotechnical properties could be both cost effective and provide superior levels of safety and physical security. The bedrock adjacent to and enclosing the reactor chamber would become the functional equivalent of a conventional containment structure, but one with increased margins of safety for design-basis accidents, reduced risks for beyond-design-basis accidents, and a high level of inherent physical protection against external threats. In addition, seismic safety could be enhanced at lower cost because seismic waves are generally attenuated with depth in bedrock. Nominal steel and concrete around the reactor would be required as would sealing of tunnels and other penetrations into the reactor chamber. Nonetheless, the net result in capital cost savings could potentially more than offset the cost of underground excavation. For a hypothetical granitic bedrock site with SMRs at a nominal depth of 100 meters, preliminary excavation cost estimates for single- and four-unit installations constructed by drill-and-blast range from around $90 million to $45 million per reactor, respectively, and for a twelve-unit installation constructed by tunnel boring machine from $25 to $15 million per reactor. Specialized applications for bedrock-sited SMRs include collocation at underground hydropower stations, test and demonstration facility for prototype SMR designs, and deployments in regions at risk of terrorist or military attack.

Underground Siting of Small Modular Reactors: Rationale, Concepts, and Applications

Presentation at
ASME Small Modular Reactors Symposium

September 28 – 30, 2011
Washington, DC

Wes Myers
Laboratory Affiliate
Los Alamos National Laboratory
myerswes@msn.com

James M. Mahar
Professor of Geotechnical Engineering
Idaho State University
mahajame@isu.edu

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"Twenty-five years after Chernobyl and in the aftermath of Fukushima, I believe it is high time to take a hard look at ... strengthening nuclear safety and security," U.N. Secretary-General Ban Ki-moon, as quoted in MIT Technology Review, May 18, 2011.

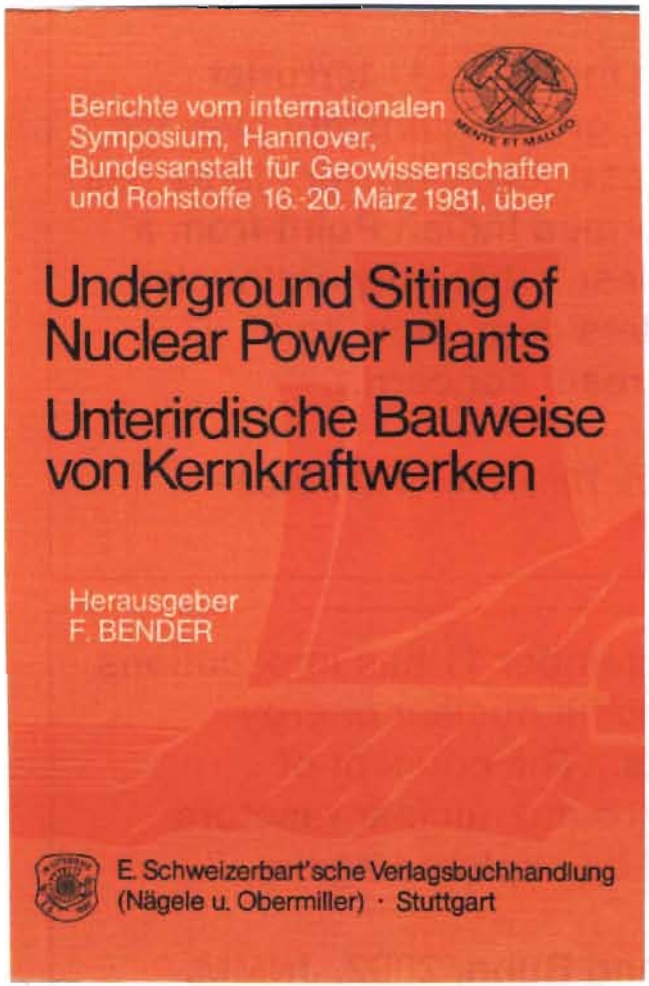
This Presentation

- Purpose. Raise awareness of the potential for deep underground (bedrock) siting of SMRs to contribute to emerging opportunities for SMR deployments

- Topics:
  - **Superior safety and physical security**
  - **Excavation cost estimates for single- and multi-unit installations**
  - **Unique applications**

Detailed Studies in the 1970s

Hannover Symposium



Conclusions related to bedrock siting

Within the technical and engineering state-of-the-art

"...concept is practically feasible..."

Potential for greatly improved:

- **containment under severe accident conditions**
- **physical security**
- **protection against earthquake damage.**

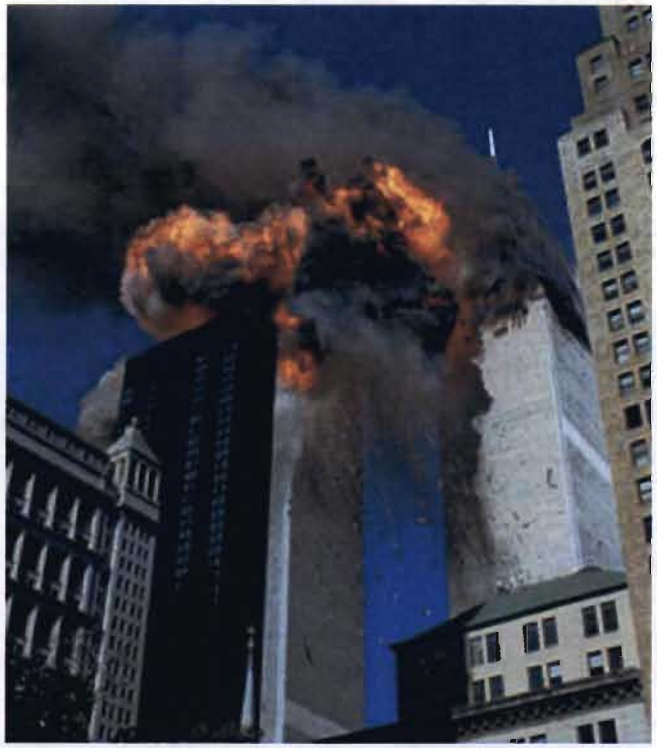
Other advantages: Public Acceptance...Radiation Shielding...Tornado/Hurricane Resistance...Uniform Working Conditions...Landscape Aesthetics

- **Cost was the issue...**

Study Sponsor	Depth (meters)	Construction Cost Penalty
California Energy Commission	100	**50-60%(FOAK)** **3%-10% (Nth plant)**
Ontario Hydro	450	**31-36%**
Swiss Federal Institute for Reactor Research	--	**11-15%**
Japanese Ministry of Trade and Industry	150	**20%**

Underground siting received only modest attention from 1980s to early 2000s.

Then….



" Since the Sept. 11 terrorist attacks, growing anxiety over the safety of nuclear power plants has transformed Indian Point from a fringe issue that only antinuclear crusaders care about to a mainstream concern… "

New York Times, April 24, 2002

"…September 11 has implications for specific nuclear energy choices…The concept of underground nuclear reactors should be explored again…"

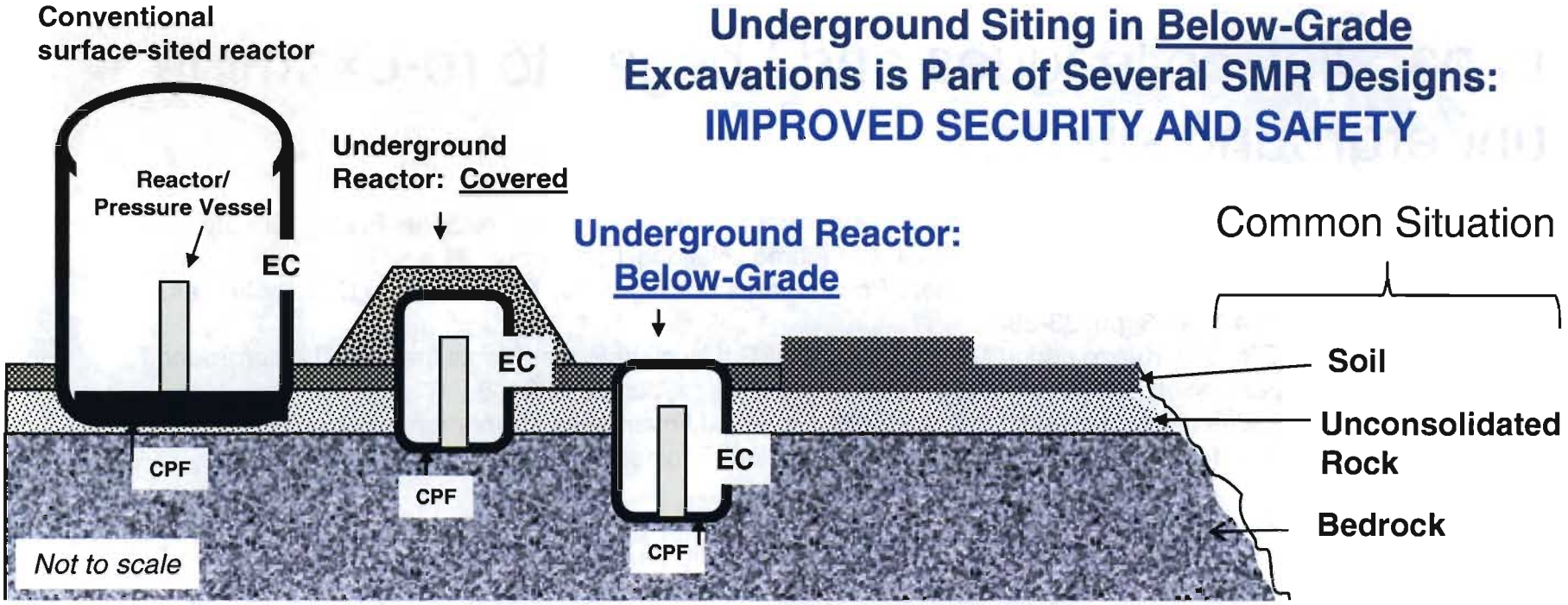
Bunn and Bunn, 2002, JNMM.

In parallel, colleagues and I began to re-examine underground siting...

- Myers, W. and N. Elkins, 2003, "Concept for an Underground Nuclear Park and National Energy Supply Complex at Carlsbad, New Mexico," LA-14064, Los Alamos National Laboratory. 39 p.
- Myers, W. and N. Elkins, 2004, "Siting Nuclear Power Plants Underground: Old Idea, New Circumstances," *Nuclear News,* v. 47, no. 3, pp. 33-38.
- Myers, W., N. Elkins, J. Kunze and J. Mahar, 2006, "DD&R if Nuclear Power Plants are Sited Underground," American Nuclear Society, 2006 Annual Meeting, Reno, Nevada, June 4-8, 2006.
- Myers, W., N. Elkins, J. Kunze, and J. Mahar, 2006, "Potential Advantages of Underground Nuclear Parks," Proceedings of the 14th International Conference on Nuclear Engineering, 14-8913, Miami, Florida, July, 17-20, 2006.
- Mahar, James, M., Jay F. Kunze, Carl W. Myers, and Ryan Loveland, 2007, "Advantages of Co-Located Spent Fuel, Reprocessing, Repository and Underground Reactor Facilities," American Nuclear Society, Advanced Nuclear Fuel Cycles and Systems, Boise, Idaho, September 9 – 13, 2007
- Mahar, James M., Jay F. Kunze, and Carl W. Myers, 2008, "Underground Nuclear Parks- Power Plant Design Implications," Proceedings of the 16th International Conference on Nuclear Engineering, Orlando, Florida, May 11-15, 2008.
- Myers, C. W., J. F. Kunze, J. M. Mahar, and N. Z. Elkins, 2008, "Underground nuclear parks; new approach for the deployment of nuclear energy systems," in *Underground Spaces – Design, Engineering and Environmental Aspects,* C. A. Brebbia, D. Kaliampakos and P. Prochazka, Eds. (WIT Press, Ashurst Lodge, Ashurst, Southhampton, United Kingdom) pp. 63 – 70.
- Giraud, K. M., J F. Kunze, J. M. Mahar and C.W. Myers, 2009, "Cost Advantages of Large Underground Nuclear Power Parks," American Nuclear Society, Annual Meeting, Atlanta, GA, June 14 – 18, 2009.
- Kunze, J.F., J.M. Mahar, K. M. Giraud, and C.W. Myers, 2010, "Underground Nuclear Energy Complexes – Technical and Economic Advantages," International Mechanical Engineering Congress and Exhibition, November 12 – 18, 2010, Vancouver, British Columbia.
- Giraud, K. M., J. F. Kunze, J. M. Mahar, and C. W. Myers, "Below the Horizon," Focus on Power and Energy article, *Mechanical Engineering Magazine*, December 2010.

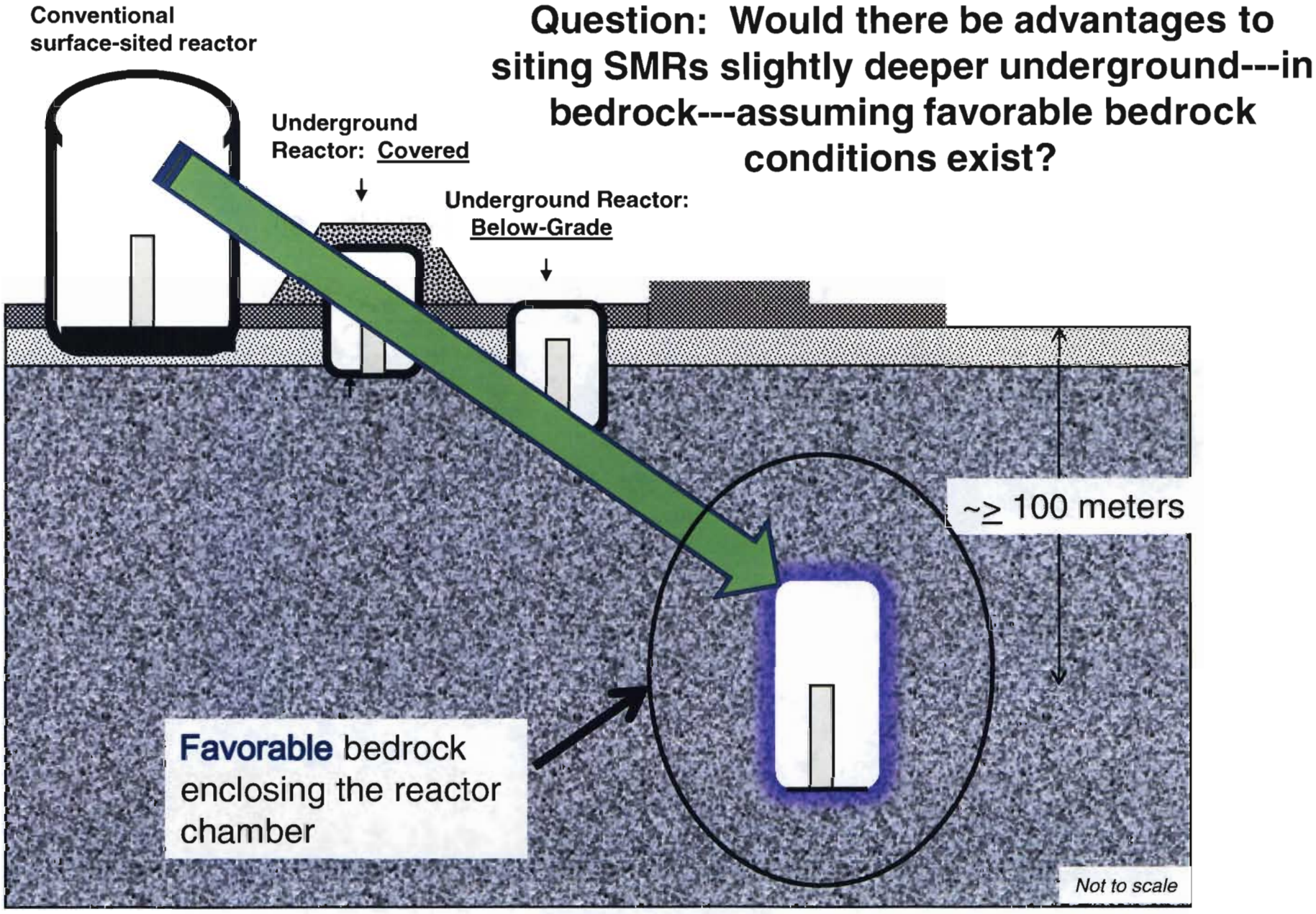
…and recently, SMRs specifically

Underground Siting in Below-Grade Excavations is Part of Several SMR Designs: IMPROVED SECURITY AND SAFETY



- **mPower**: "Put vulnerable structures underground where they are much easier to protect and exposed to things like airplane strikes."
- **Holtec HI-SMUR**: "…principal safety credentials derive from locating the core underground…"
- **Hyperion**: "Sited underground, out of sight"
- **NuScale**: "…Reactor Vessel... Located below grade…"
- **Toshiba 4S**: "… proposing to bury their reactor nearly 100 feet (30 meters) under ground…"
- **PRISM**: "…will be built underground on seismic isolators…"

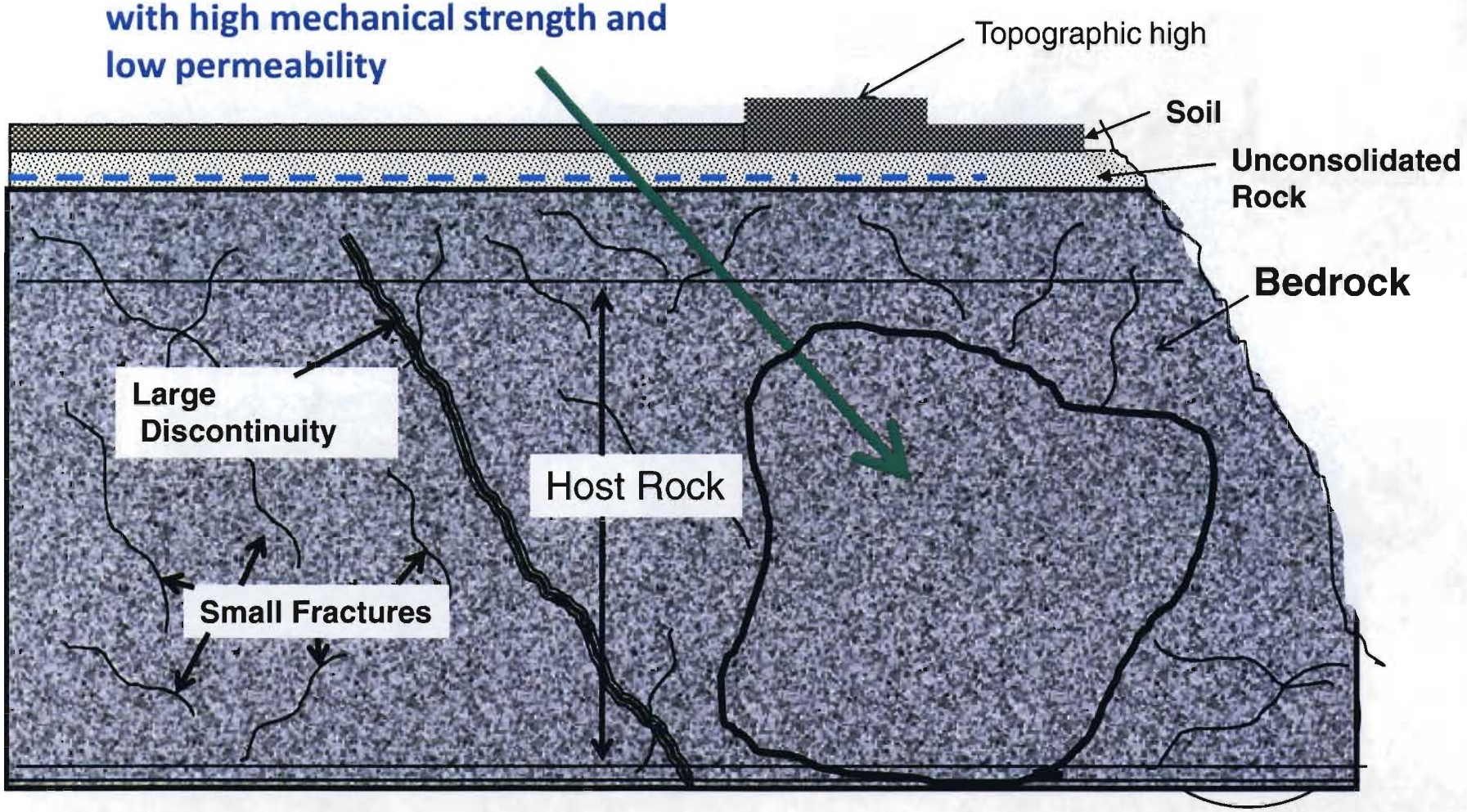
EC=Engineered Containment Structure,
CPF=Concrete Pad Foundation



Question: Would there be advantages to siting SMRs slightly deeper underground---in bedrock---assuming favorable bedrock conditions exist?

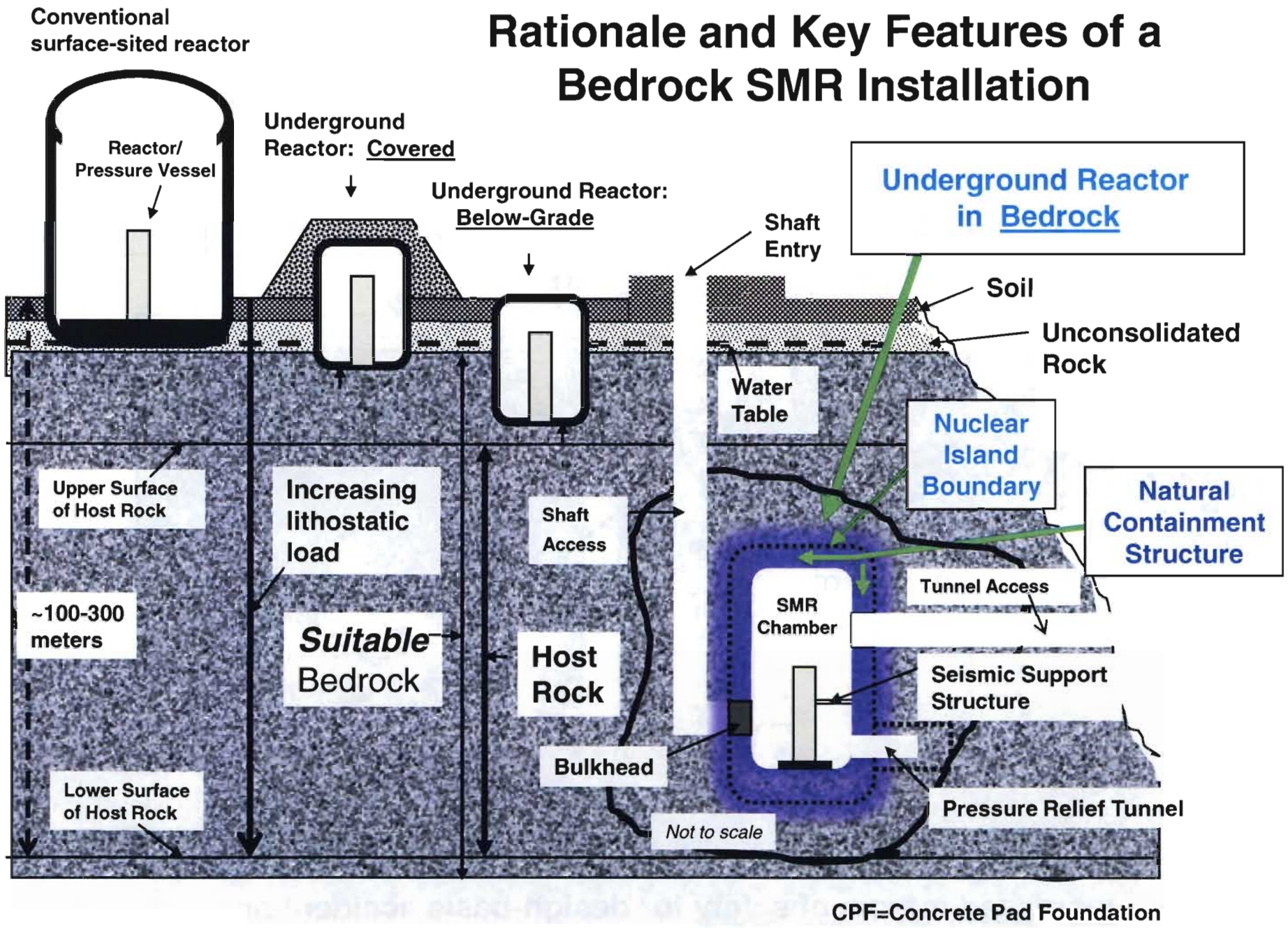
Hypothetical Site - Survey Results

Sufficient volume of host rock , generally free of discontinuities, with high mechanical strength and low permeability

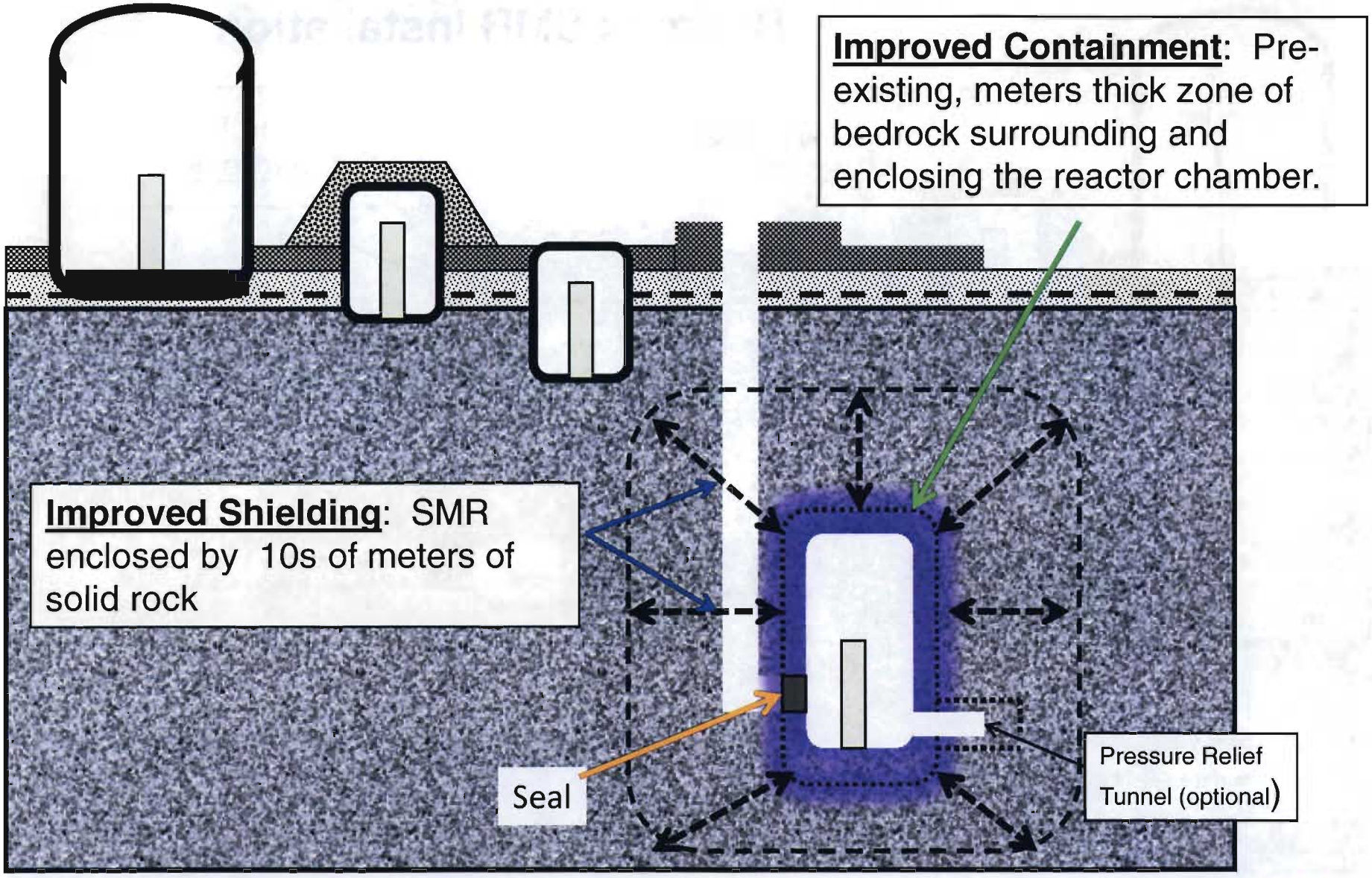


Earth materials are never completely homogeneous and isotropic

Rationale and Key Features of a Bedrock SMR Installation

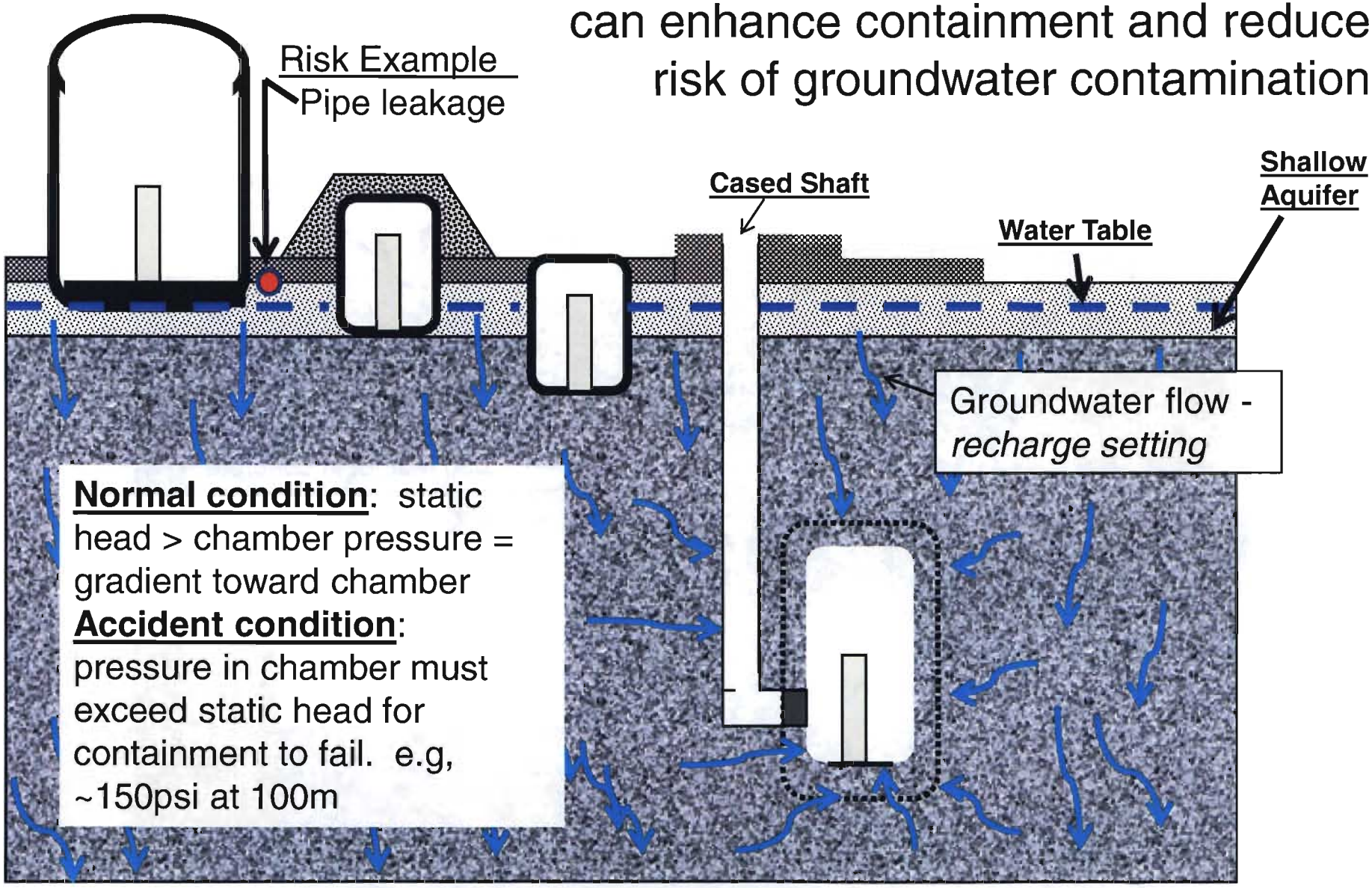


Safety Advantage: Greater Defense-in-Depth



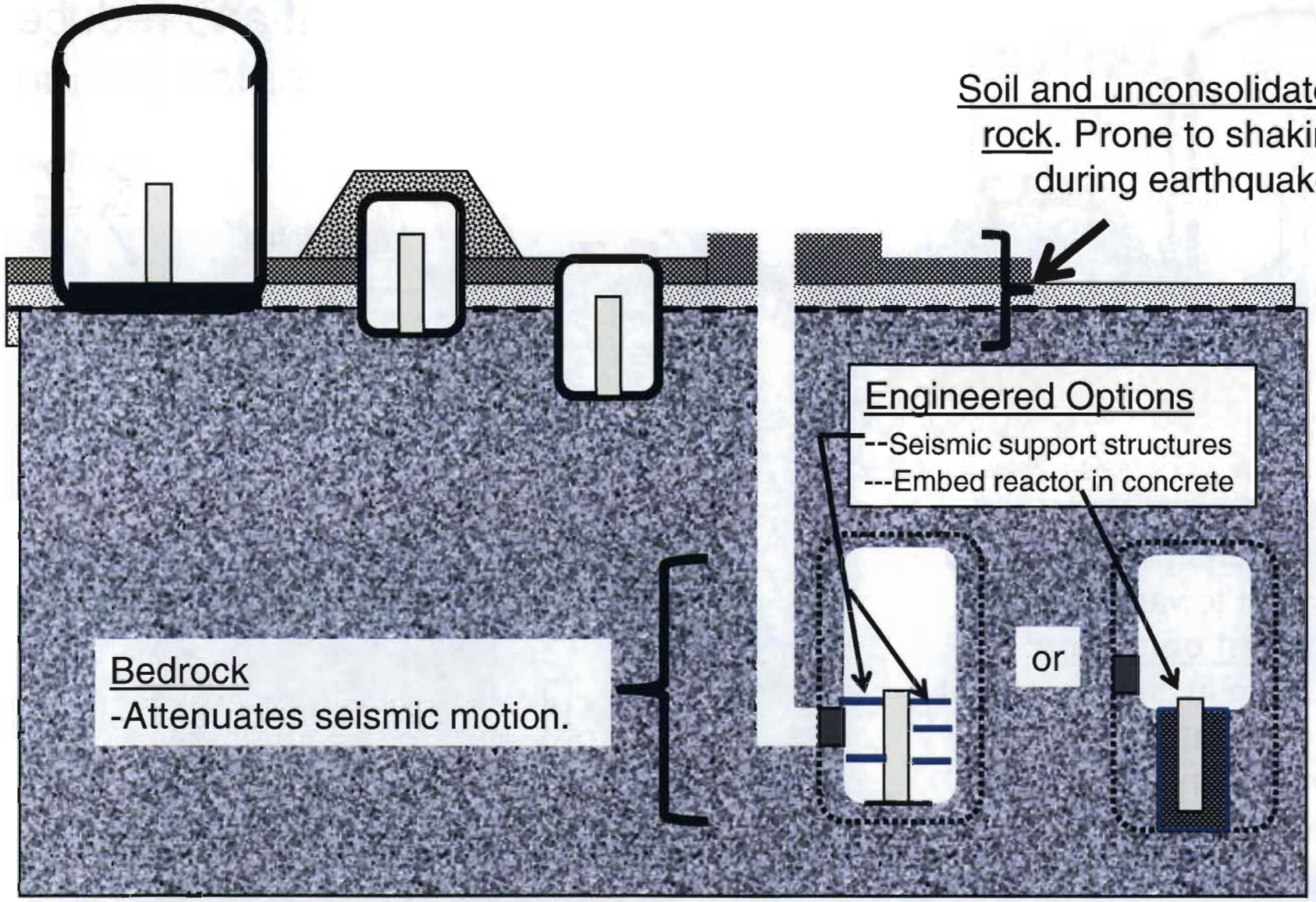
Result: Increased margin of safety for design-basis accident and reduced risk for beyond-design-basis accident.

Safety Advantage: Natural geo-hydrologic phenomena can enhance containment and reduce risk of groundwater contamination



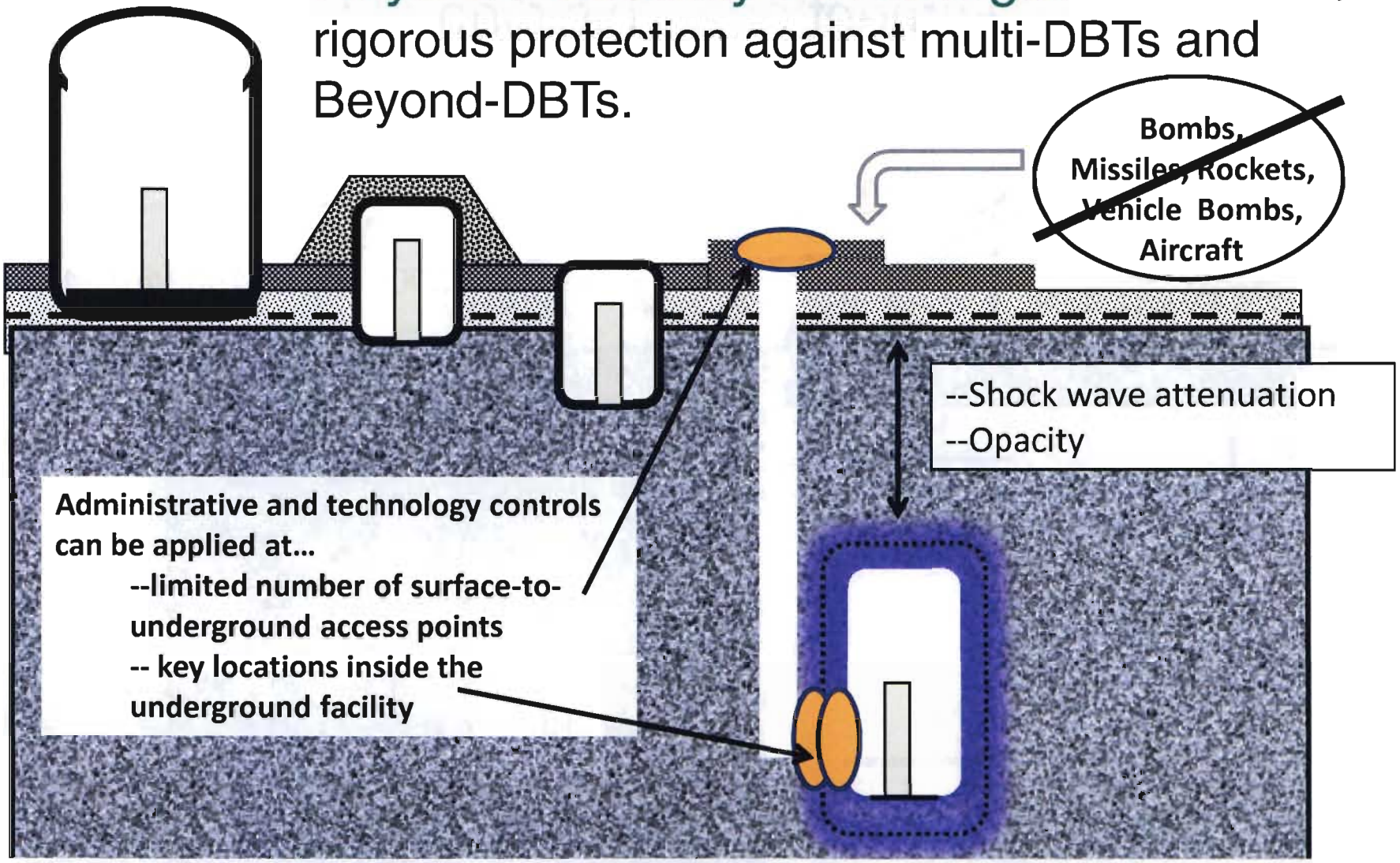
Result: improved containment…reduced risk of leakage into shallow aquifer

Safety Advantage: Improved earthquake resistance



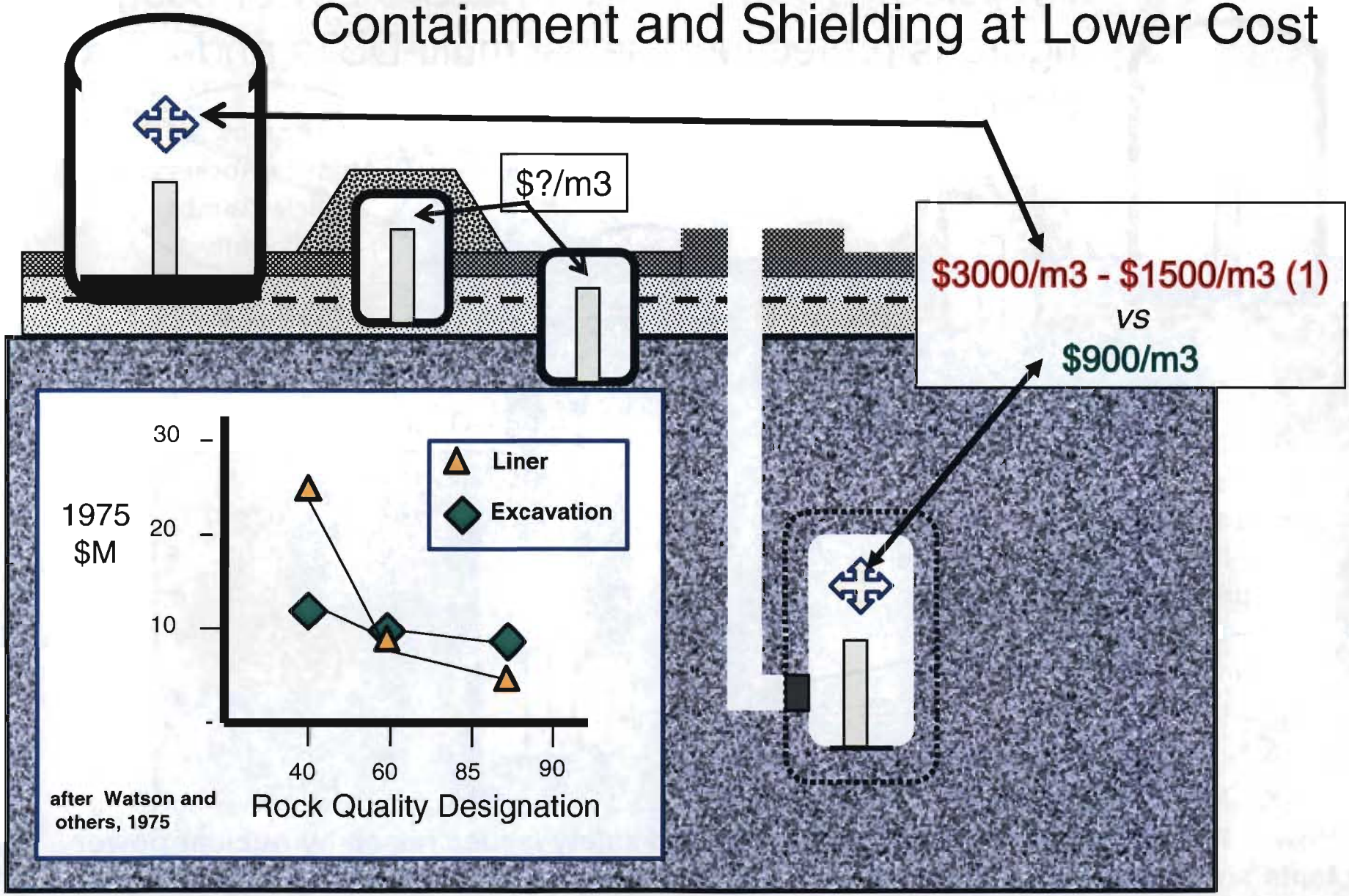
Result: greater safety and lower cost to protect against the design basis earthquake.

Physical Security Advantage: Lower-cost, rigorous protection against multi-DBTs and Beyond-DBTs.



"How is it that the anxiety over the security and safety issues raised by nuclear power plants so seldom expresses itself as a demand that they be built underground?"
(F. Hapgood, 2006, "Security Holes," csoonline.com)

Potential Cost Advantage : Improved Containment and Shielding at Lower Cost



(1) Assumes $6000/kw - $3000/kw construction cost with 5% for containment structure

Concept for a Single-Unit SMR Installation--

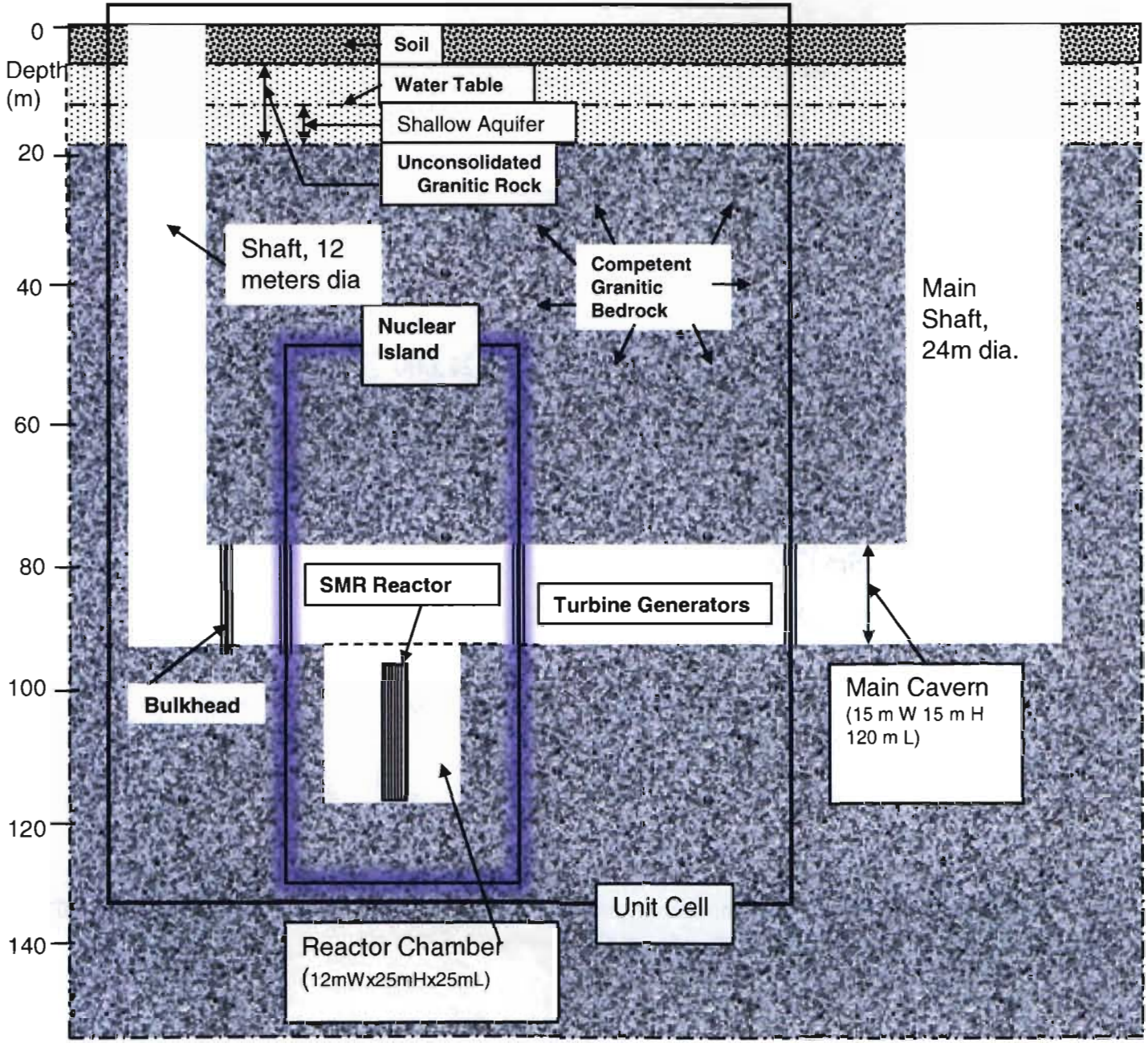
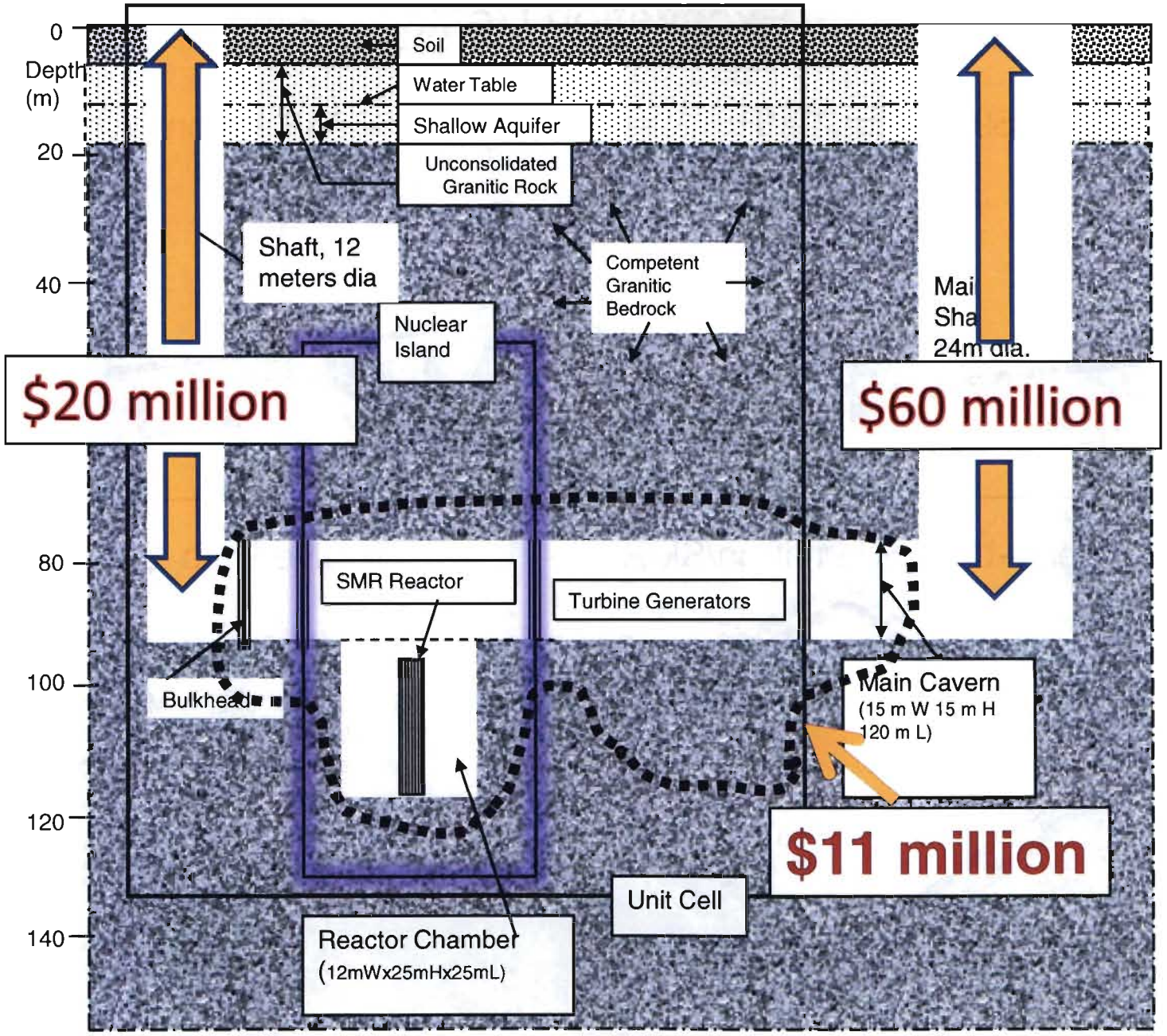


TABLE 1
Preliminary Excavation Cost Estimates

	Nominal Dimensions (meters)	Volume (cubic meters)		Cost* ($million)
Shafts				
Main Shaft	24m dia 90m deep	--------		**60**
Secondary Shaft	12m dia 90m deep	--------		**20**
			Subtotal	**80**
Main Cavern	15mW 15m H 120mL	27,000		**2.0**
Pressure Vessel Chamber (1)	12mW 25m H 25m L	6,750		**6.8**
Condenser	22mx27mx 30m	17,800		**1.4**
Spent Fuel Pool	45mx80mx 140m	14,200		**1.1**
			Subtotal	**11.3**
			Total	**91.3**

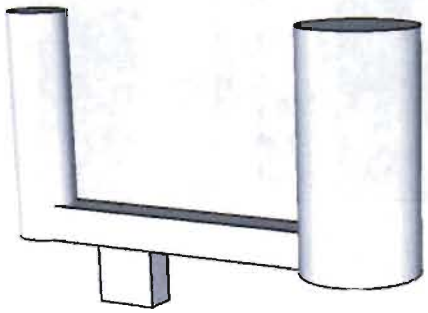
***Excavation cost of main shaft, secondary shaft, condenser, and spent fuel pool are from Mahar and others (2007). Unit cost of main cavern excavation is $75/m3. Unit cost of pressure vessel excavation is $900/m3.**

Major Excavation Cost Elements

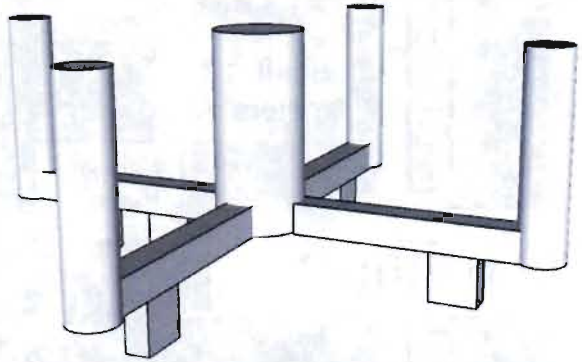


Concepts for Multi-Unit SMR Installations: Excavation Costs

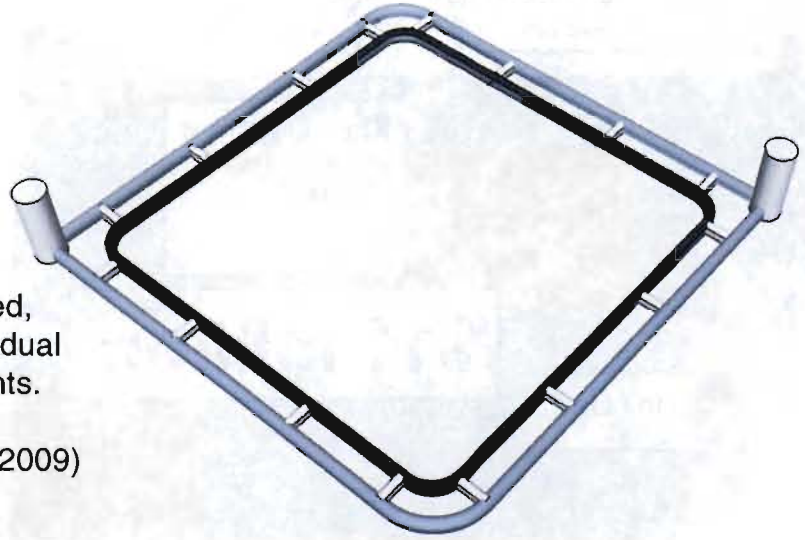
Single-Unit: $90 million/SMR



Four-Unit: $45 million/SMR



Twelve-Unit: $25 million/SMR



TBM Excavated, SMRs in individual tunnel segments.

(After Giraud, 2009)

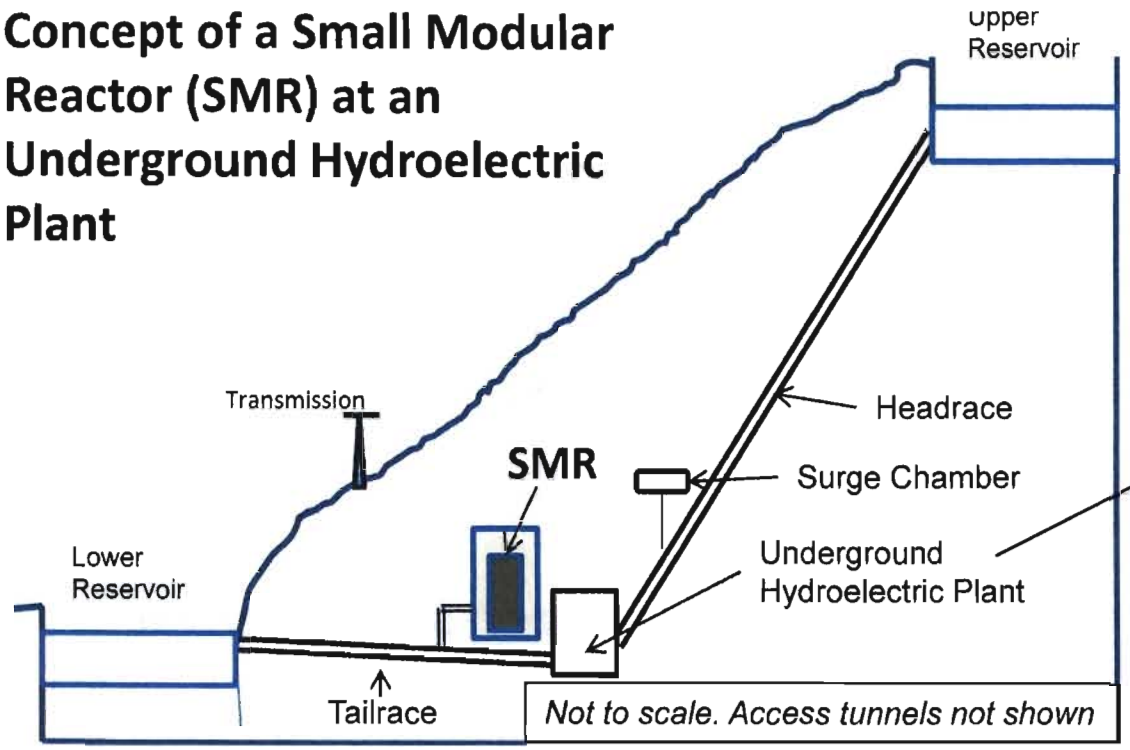
Twelve-Unit: $12 million/SMR

(Not shown)

Reduce length of TBM segments, site SMRs in common tunnel chamber, and assume 60% cost reduction

Possible Specialized Applications

1. Collocation of SMRs at Underground Hydroelectric Plants



Manapouri Power Station, New Zealand

Advantages: Secure, Safe, Incremental Capacity Additions
--Underground access and Transmission access
--Suitable bedrock
--Tailrace water for cooling

2. Test and Demonstration Facility for Prototype SMR Designs

3. Nations or Regions at Risk of Terrorist or Military Attack

Final Points

"I am convinced that if the Fukushima plants in Japan had been underground they would not have sustained so much damage from the tsunami and would not have developed into such a disaster. In fact, they may not have been damaged at all"
Gunnar Nord, Senior Advisor in Tunneling, Atlas Copco, *Mining and Construction Online*, July 19, 2011.

Bedrock siting of SMRs could be a credible, preferred alternative at locations where there is both the need for SMRs and <u>suitable bedrock conditions</u>---and especially where either:

- **<u>safety and physical security concerns</u> are paramount**

  or
- **Conventional surface-siting or below-grade siting involves <u>high capital, operating or decommissioning cost</u>.**

<u>FAQs</u>
Earthquakes?
Groundwater Contamination?
Size of Underground Openings?
Cultural Barriers?

<u>Many issues need study, examples</u>
…ventilation, fire, emergency egress,
… piping lengths, adequate space for operations and maintenance…
…much more work on the economics